Detecting supernova neutrinos at SNO+

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IOP HEPP & APP Annual Conference

06/04/2022

UNIVERSITY OF SUSSEX

Introduction

In this talk:

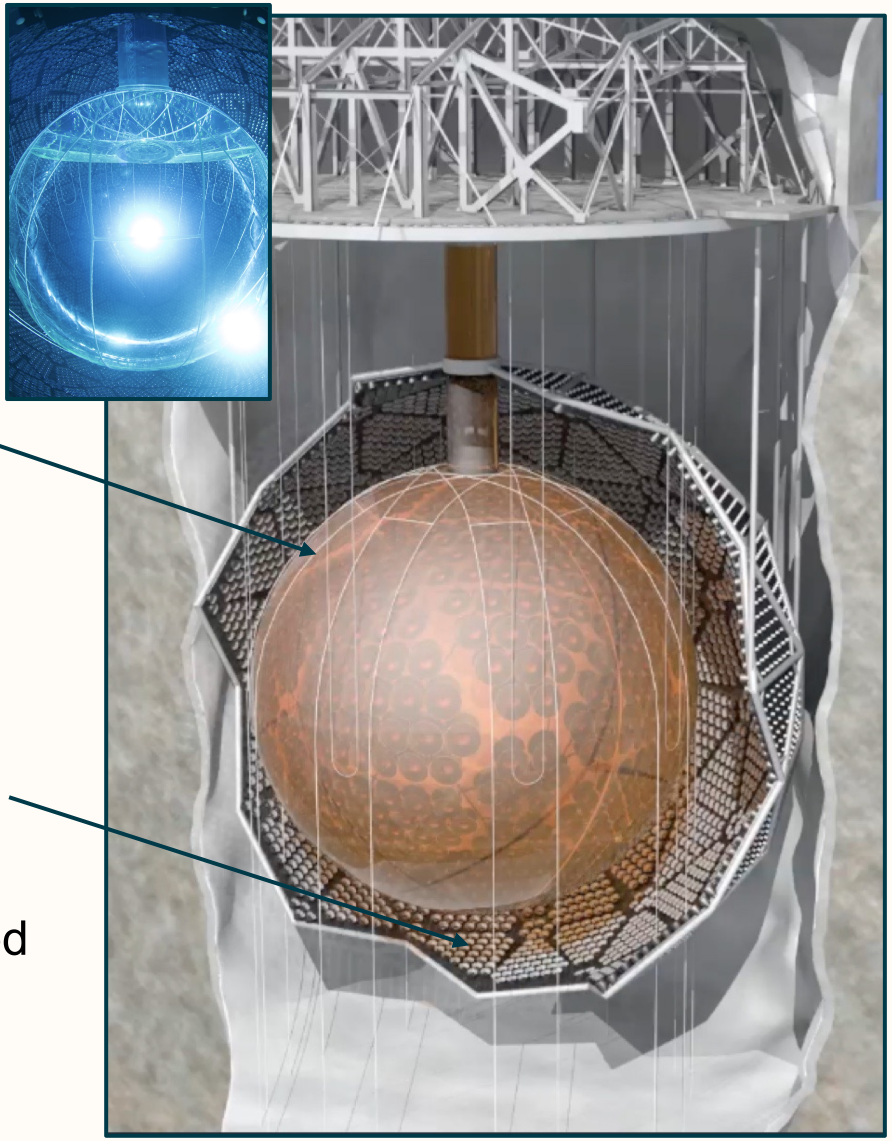
- SNO+ Experiment
- What is a supernova?
- How do supernova neutrinos interact with SNO+?
- How do we detect supernova neutrinos?
- Outline of potential physics we can learn

SNO+ Experiment

- Upgrade from Sudbury Neutrino Experiment (SNO) which won the Nobel Prize in Physics in 2015.
  https://www.nobelprize.org/uploads/2018/06/mcdonald-lecture-slides.pdf
- Housed in SNOLAB, Sudbury, Canada.
- Multi-purpose neutrino experiment.
  - Primary research goal is neutrinoless double-beta decay ($0\nu\beta\beta$).
  - Broad physics program includes, solar and reactor neutrino oscillations, geoneutrinos and ***supernova neutrino detection***, nucleon decay, and dark matter detection
- Albanese, V., et al. "The SNO+ experiment." *Journal of Instrumentation* 16.08 (2021): P08059. https://arxiv.org/abs/2104.11687

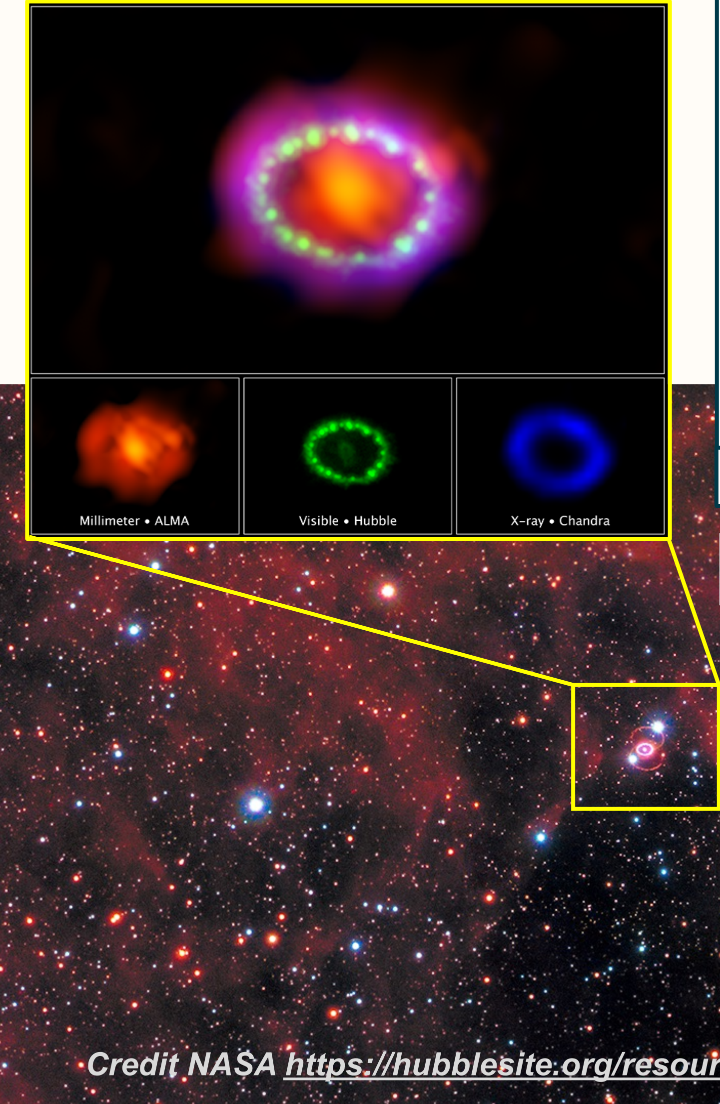
SNO+ Detector

- 2 km underground, ~6000 MWE
- 12 m diameter Acrylic Vessel (AV):
  - Filled with 780 tonnes of liquid scintillator:
    - LAB + [target of] 2 g/L PPO
    - To be loaded with ^{130}Te for double beta decay studies
- Surrounded by 7 kT of external ultra-pure water
- Viewed by ~9300 (8”) PMTs mounted on a 17 m diameter PMT support structure (PSUP)
- AV is now full filled with liquid scintillator. Currently loading PPO, planned to start adding ^{130}Te at the end of 2022



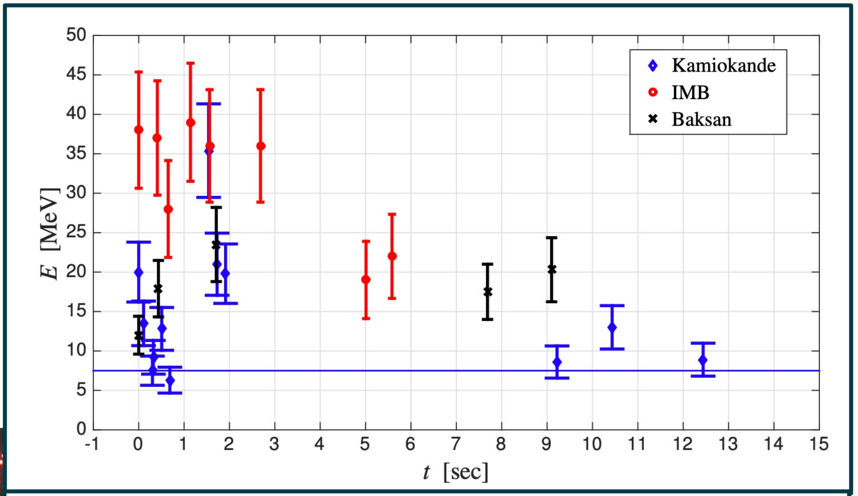
Supernovae

Sammy Valder



SN1987A

Credit NASA https://hubblesite.org/resource-gallery/images



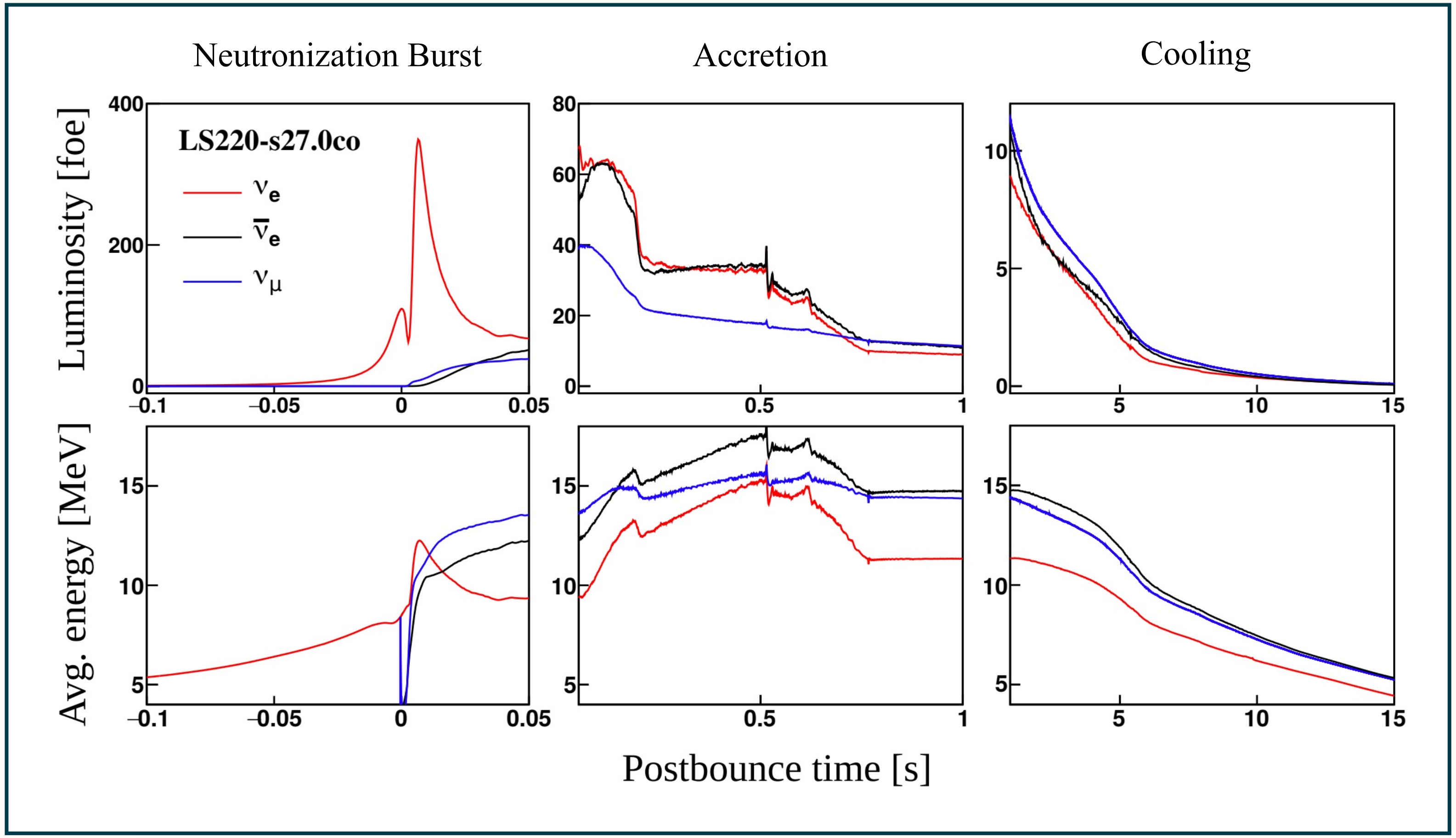
Credit: https://arxiv.org/pdf/1601.03422.pdf

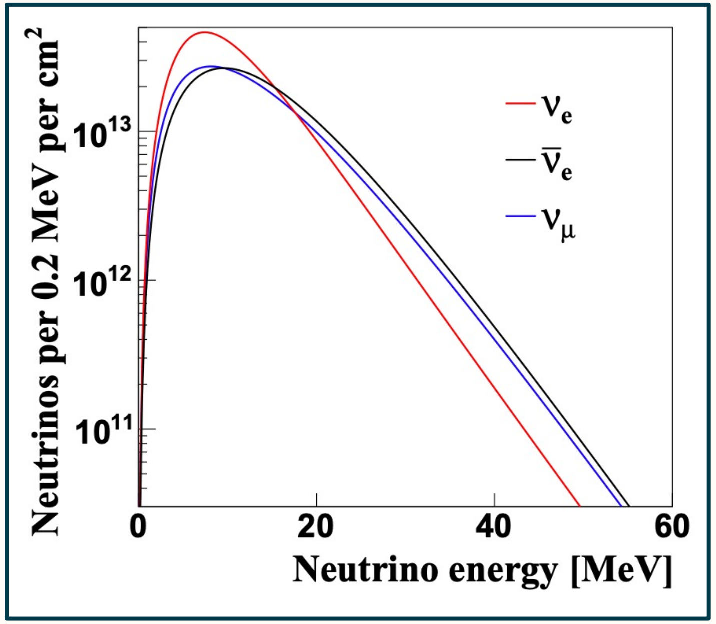
- As a massive star approaches the end of its life will likely go **supernova (SN)**
- These are some of the most powerful and luminous phenomena known to the universe
- Extremely rare within our galaxy with 1.63 ± 0.46 CCSNs per century †
- $\mathcal{O}(10^{58})$ neutrinos emitted carrying 99% of the energy
- Last observed supernova neutrinos signal occurred in 1987 (SN1987A)
- Neutrino burst lasting ~ $\mathcal{O}$(10s)

† arXiv:2009.03438

Supernova Neutrino Flux

- The flux and average energy of (anti)neutrinos exiting the supernova (right). Flux and energy convolved (left).
- Separated into three CCSN phases:
  - Neutronization
  - Accretion
  - Cooling
- [1]LS220-s27.0co is shown and is the standard model used throughout this talk

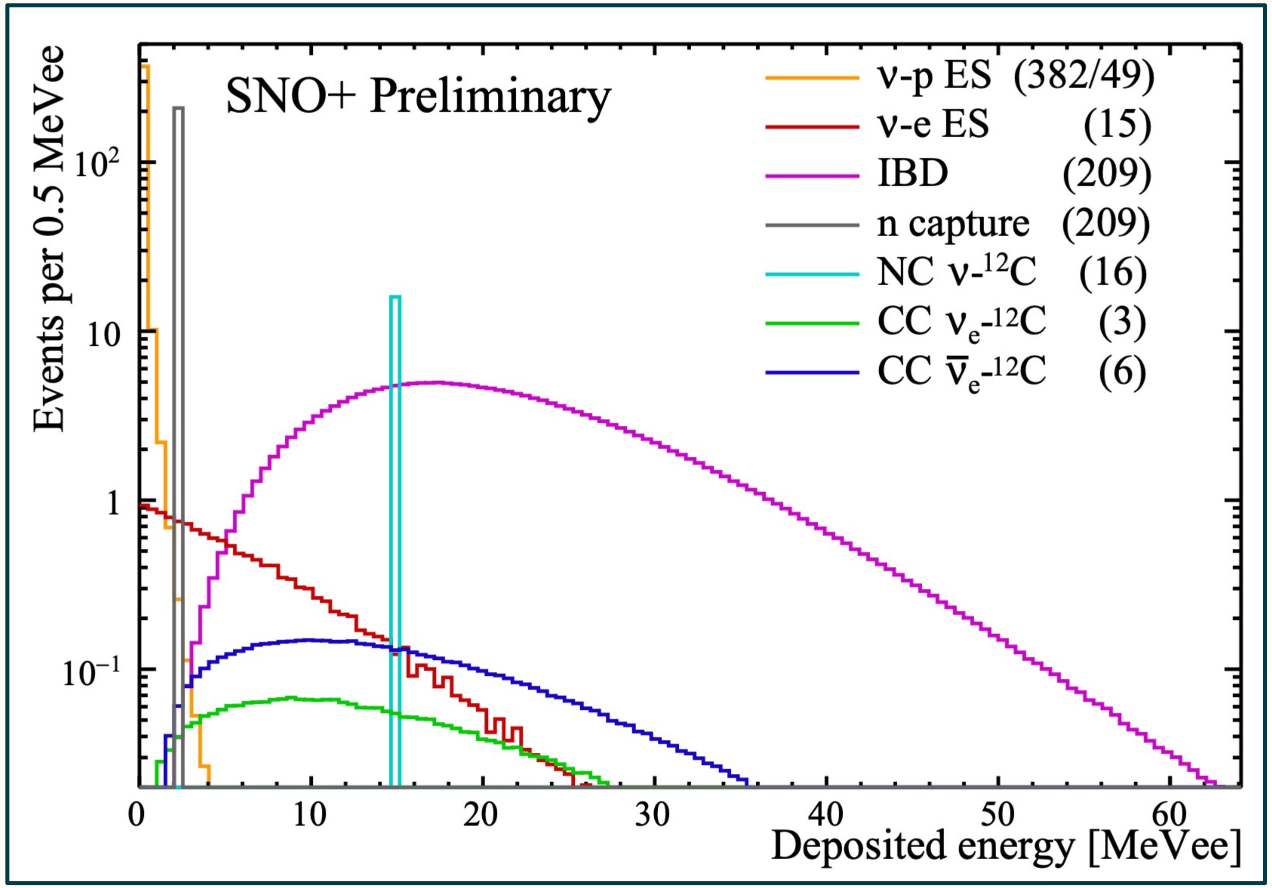




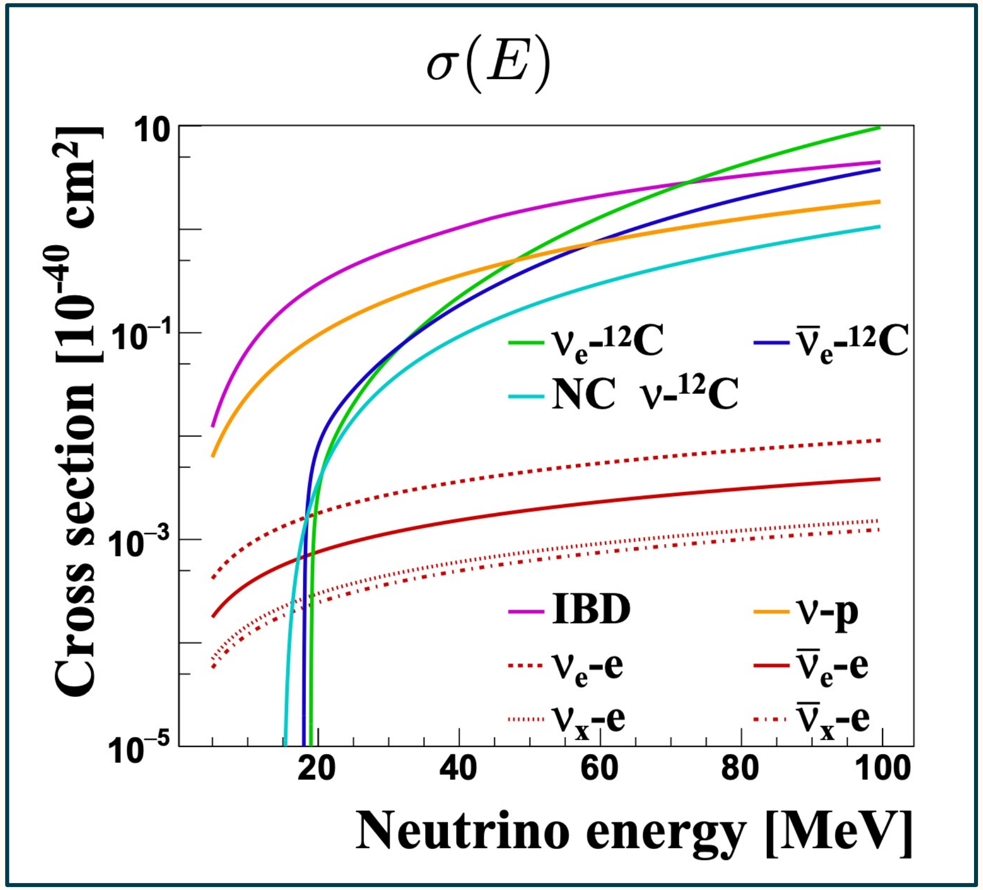
[1]Model provided by the Garching group, see: A. Mirizzi et al. Rivista del Nuovo Cimento Vol. 39 N. 1-2 (2016)

Interaction Channels

Supernova neutrino interaction channels available to SNO+ *inside* the AV

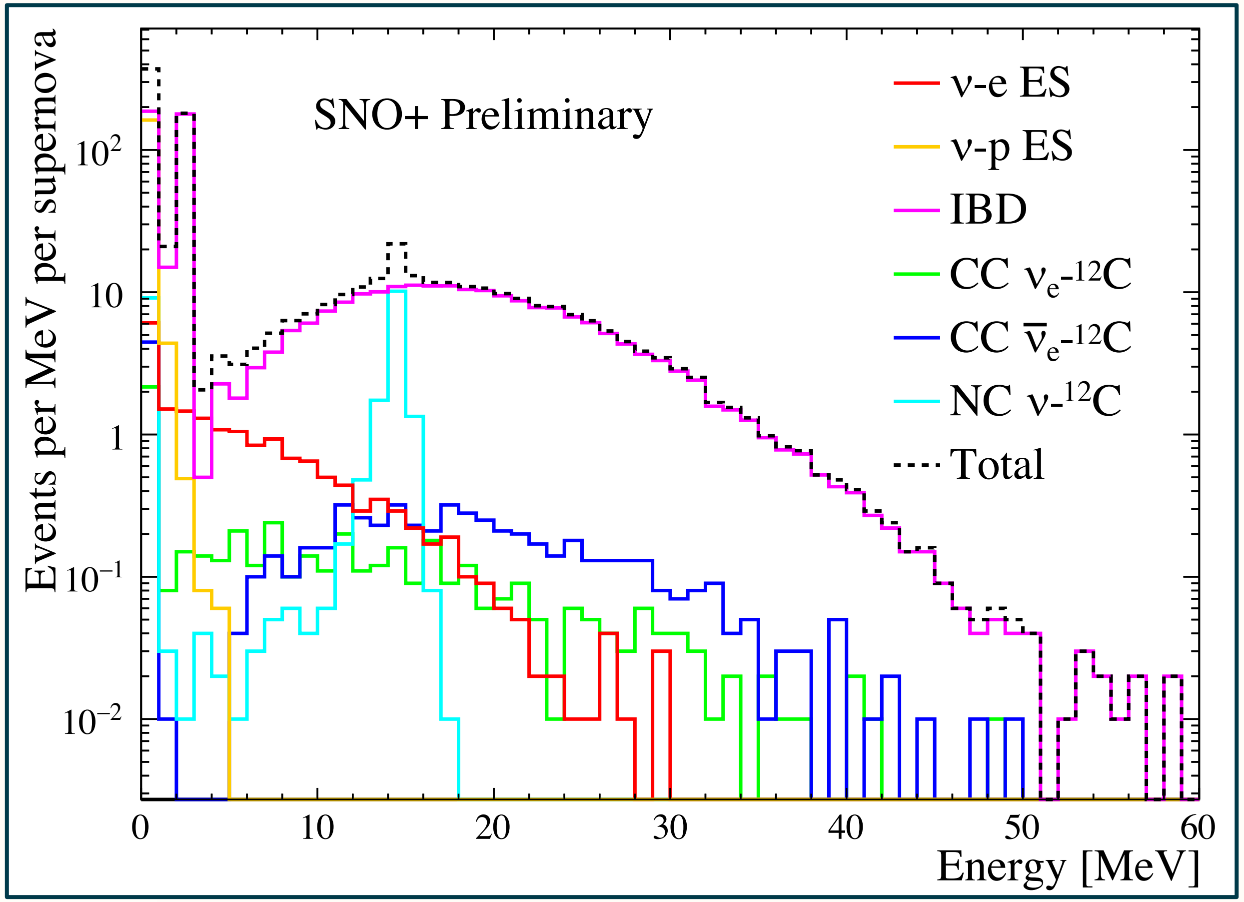


Cross-sections of interaction channels available to SNO+ *inside* the AV



Event Generation

- SNO+ recently integrated with sntools[1] to simulate supernova neutrinos in the detector
- Generated events for 100 supernovae – renormalise to predict sensitivity per example[2] supernova
- Run through detector simulation to include energy smearing and reconstruction
- Can measure NC ν-^{12}C through 15.1 MeV excitation
- Have sensitivity to ν-p elastic (NC) scattering which is unique to liquid scintillators.
    - Proton recoil spectrum can also give information about incoming ν energy

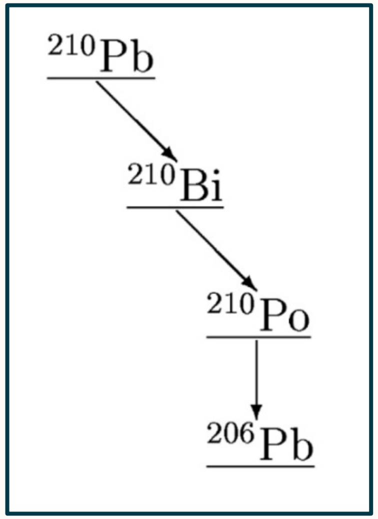


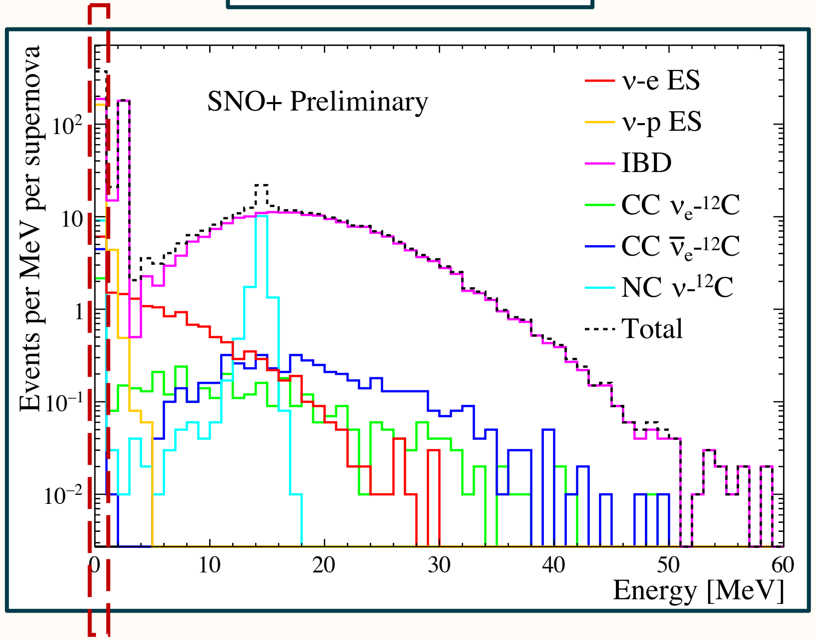
[1] Migenda et al., (2021). sntools: An event generator for supernova burst neutrinos. Journal of Open Source Software, 6(60), 2877, https://doi.org/10.21105/joss.02877

[2] A. Mirizzi et al. Rivista del Nuovo Cimento Vol. 39 N. 1-2 (2016)

[with 27M$_\odot$ progenitor CCSN with LS220 equation-of-state, at 10 kpc]

Backgrounds

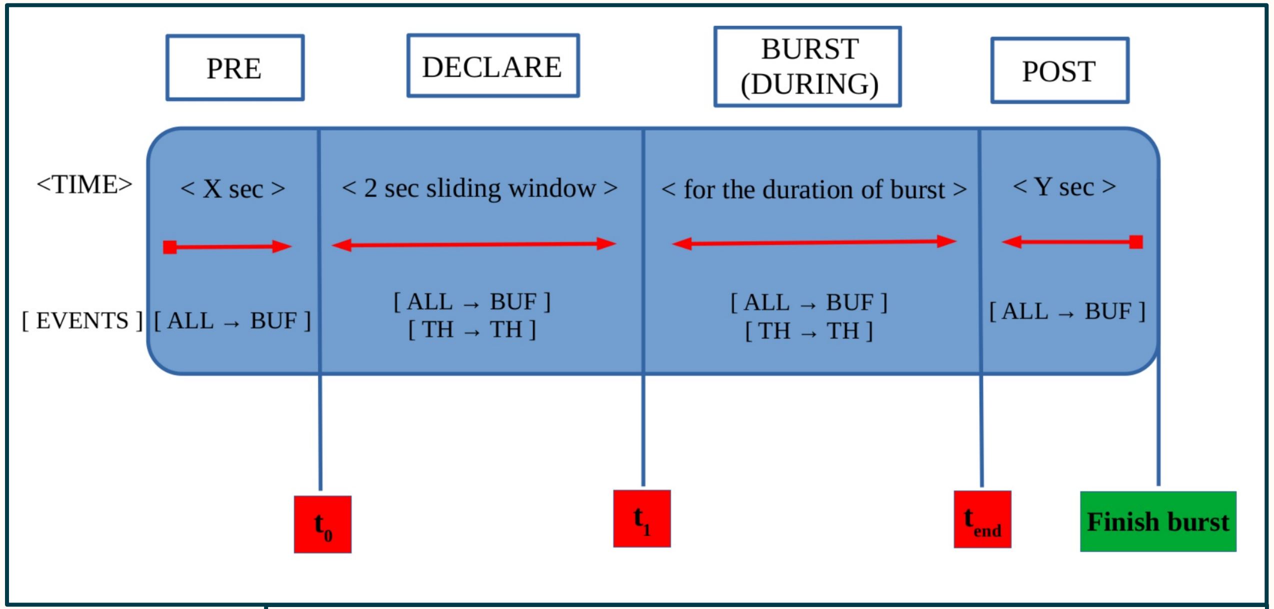




- Two main sources:
  - Intrinsic background from scintillator
  - Background from AV
- Only relevant in low energy regions < 1 MeV
  - Only affects ν-p and neutron scattering
- IBD signal is essentially background free due to neutron tagging
- Very low background likely for NC ν-^{12}C peak
- External backgrounds from other detector objects (PMTs, ropes, external water) are negligible for 5 m fiducial volume
- Re-evaluation of key backgrounds due in the near future

Burst Detection

- Looking for bursts of multiple coincident events above an energy threshold lasting $\mathcal{O}(10)$s long
- Three levels:
  - Level 1: Detect/define the bursts
  - Level 2: Analyse default observables
  - Level 3: Data cleaning
- Almost in real-time: 1-2 s latency to builder, < 30 s to analyse
- Four different buffers → allows for customisation/tuning
- Run in circular buffers to deal with boundaries
- Alarms when SN-like signal is detected:
  - Tuneable threshold values aim for ~ 1 alarm per month
- Supernova shifters on-call 24/7 for burst monitoring



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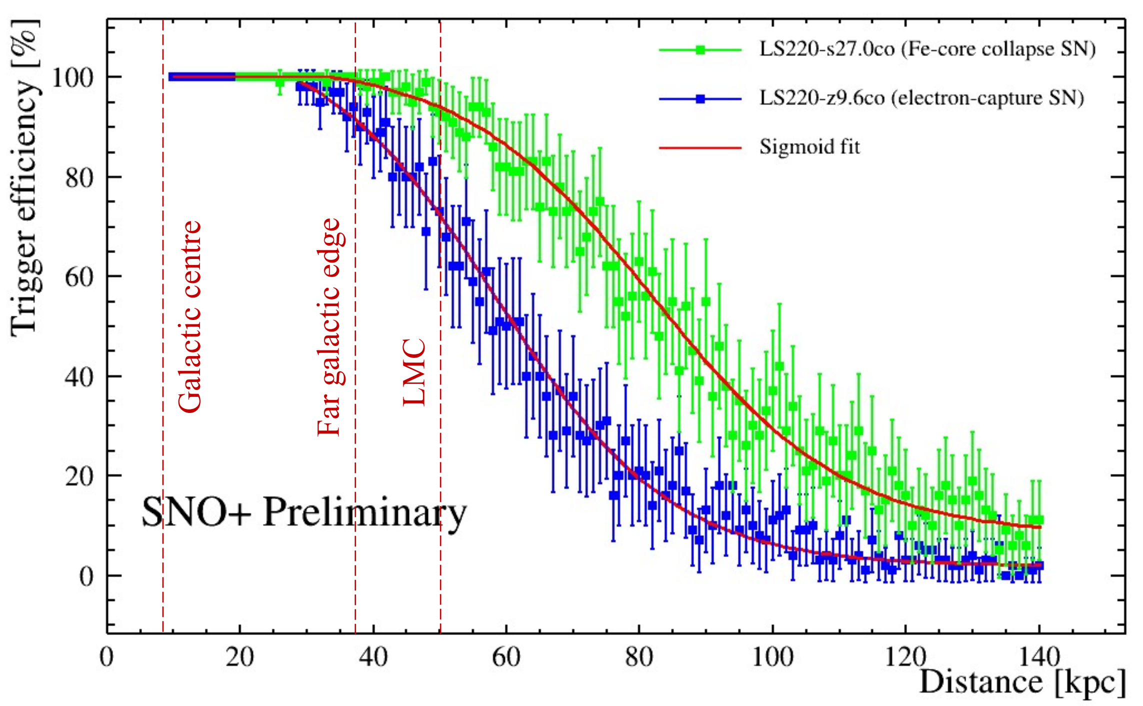
SNO+ has recently integrated with SNEWS test channel, work ongoing for SNEWS2

https://snews.bnl.gov/ https://snews2.org/

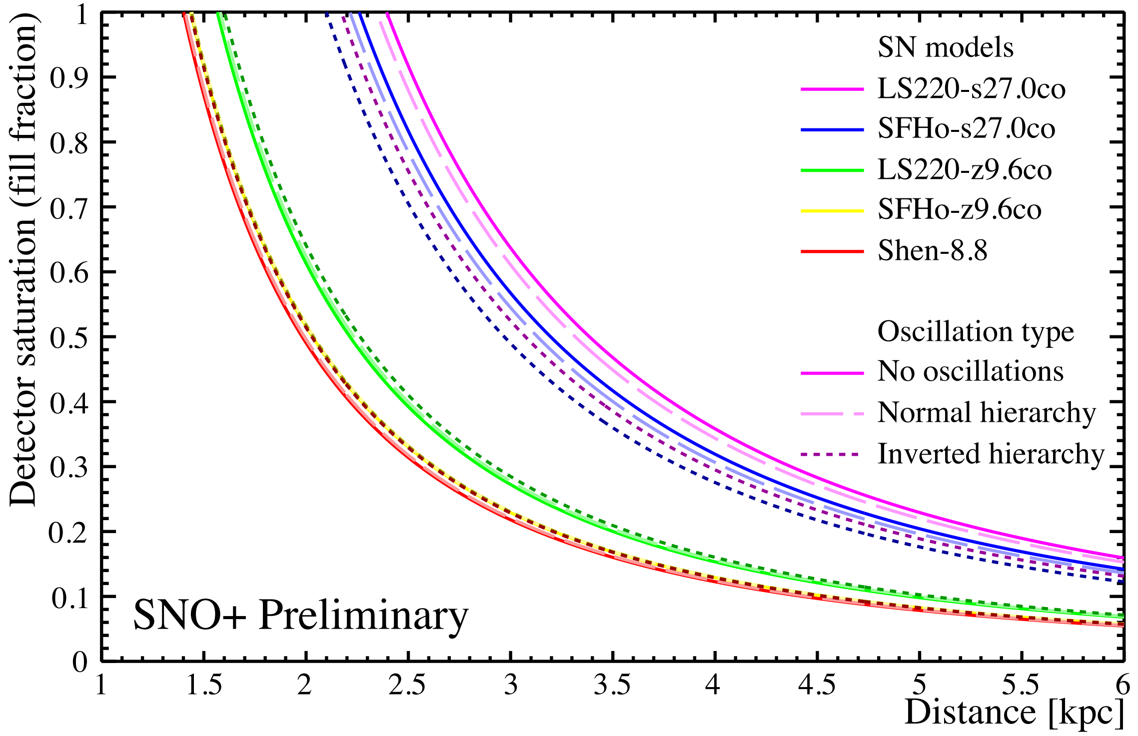
Detection Efficiency



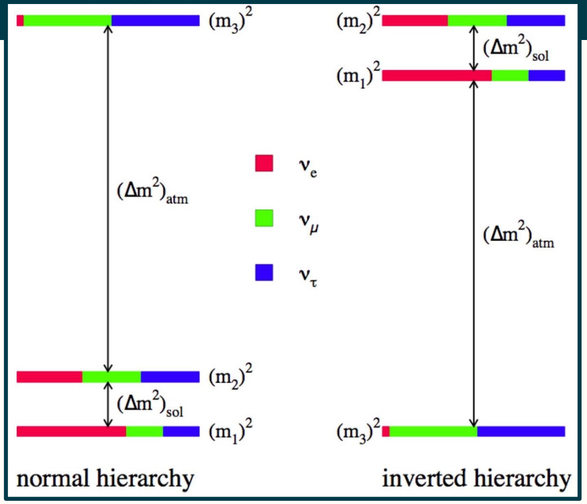
Burst trigger efficiency as a function of supernova distance

Some astronomical features are shown for context

Detector [DAQ] saturation as a function of supernova distance



Physics Program

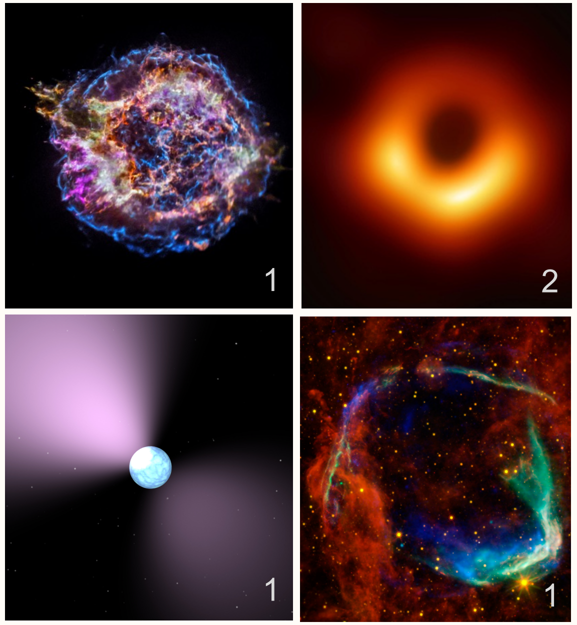


Neutrino Physics:

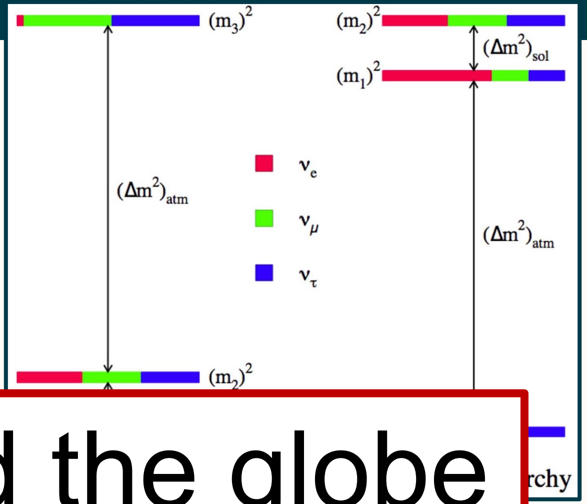
- Large source of neutrinos between 1 – 60 MeV
- Measurement of neutrino mass hierarchy through looking at beginning of the burst
- Other BSM physics, e.g. sterile neutrino search, self-interactions, neutrino mixing in dense environments, limits on ν mass/charge/magnetic moment
    - Potentially a method to distinguish Dirac vs Majorana neutrinos!

Supernova Physics:

- Supernova explosion mechanisms
- Neutron star properties
- Black hole formation → improvements to stellar evolution models



[1]Credit NASA: https://nasa.gov ; [2]Credit: Event Horizon Telescope collaboration et al.



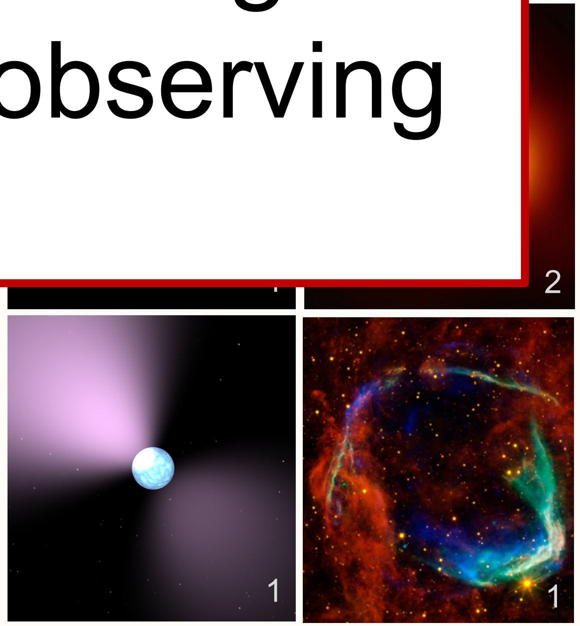
Neutrino Physics:

- Large source of neutrinos between 1 – 60 MeV
- Measurement of neutrino mass hierarchy through looking at beginning of the burst
- Oth
mix

Lots of neutrino detectors around the globe with complimentary techniques observing the same SN!

Supernova

- Supernova explosion mechanisms
- Neutron star properties
- Black hole formation → improvements to stellar evolution models



[1]Credit NASA: https://nasa.gov ; [2]Credit: Event Horizon Telescope collaboration et al.

Summary

- SNO+ is now filled with liquid scintillator → gives greater sensitivity to supernovae and access to new interaction channels
- The expected supernova signal at SNO+ is well understood
- SNO+ is a low background detector → supernova backgrounds are only prevalent < 1 MeV
- The SNO+ burst trigger is operational and has been running now for ~ 2 years
- SNO+ has excellent detection efficiency of supernova within our galaxy
- SNO+ has recently joined SNEWS, and work is in progress to integrate into SNEWS2
- Broad neutrino and astrophysical physics programs with SNO+ sensitivities to be explored

Backup

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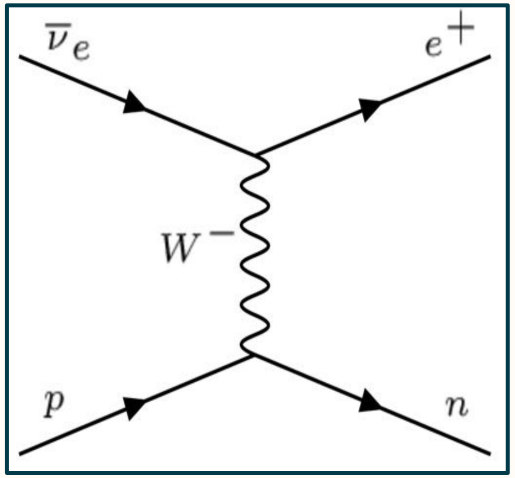
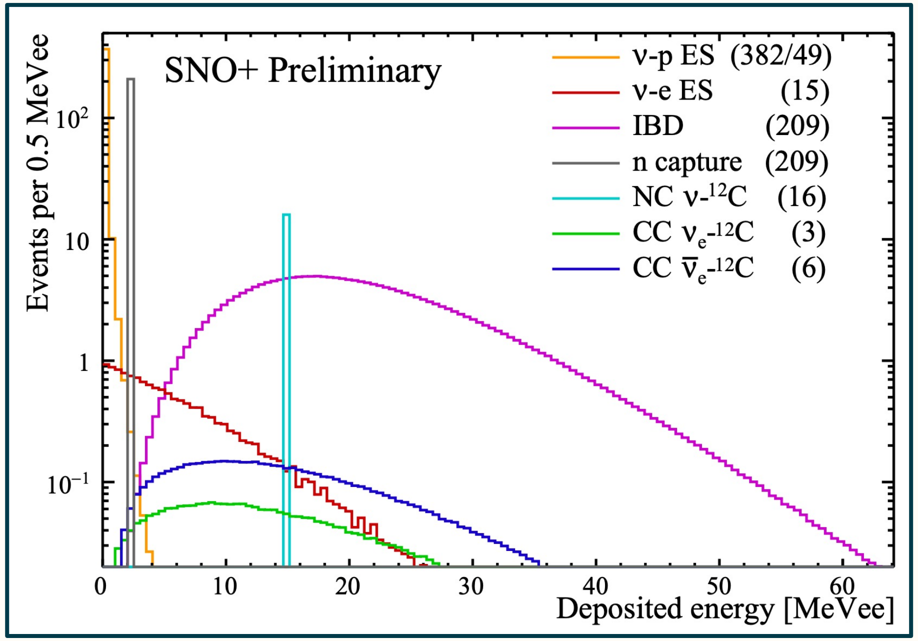
- Anti (electron)neutrino undergoes charged current (CC) interaction with proton to produce positron and neutron
- Outgoing positron detected as spectrum
- Neutron capture on proton produces 2.2 MeV delayed photon
  - Easy to tag
- Largest signal from supernovae in SNO+
  - 209 events expected from example† SN at 10 kpc

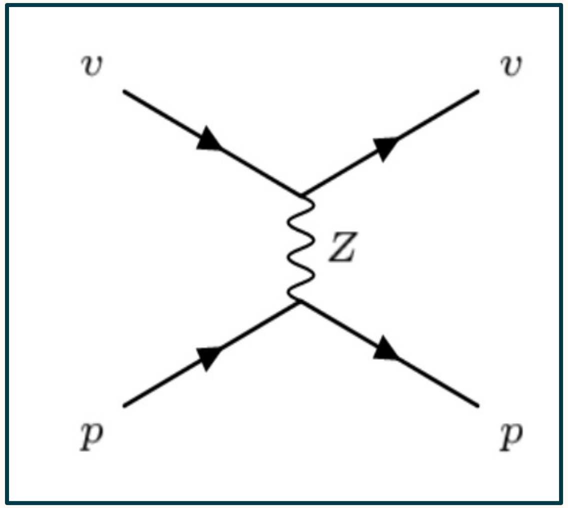


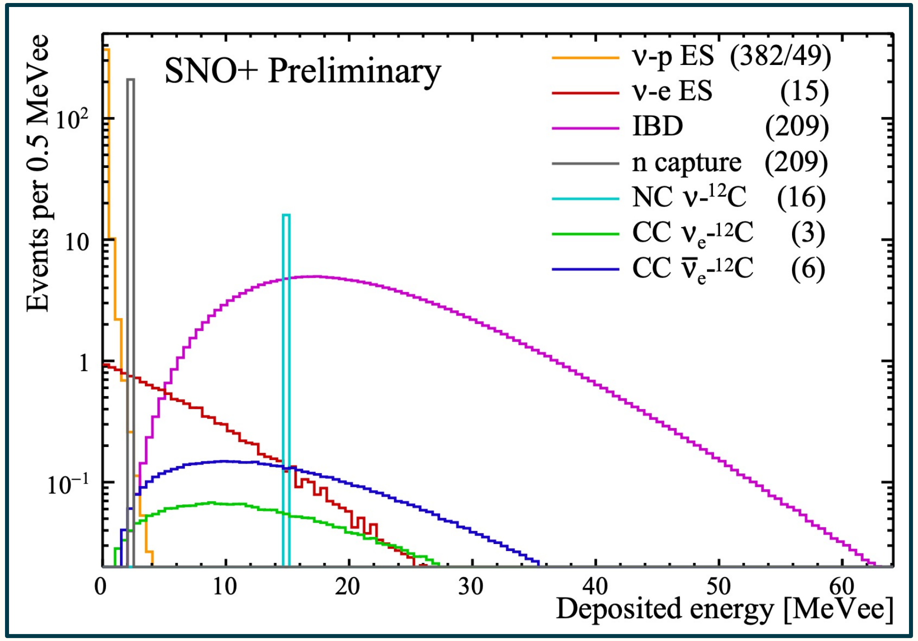


† $27M_{\odot}$ progenitor CCSN with LS220 equation-of-state

Proton Scattering

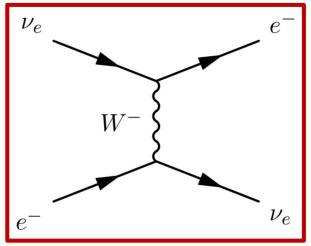
- Few MeV protons are invisible in water Cherenkov detectors, but is possible to see them in liquid scintillator → available to SNO+
- Neutral current (NC) interaction → sensitive to all neutrino flavours
- Proton recoil spectrum provides spectral information about incoming neutrino → measure neutrino energy
- Difficult to detect
- Signal will be quenched in the detector
    - 382 events predicted†, 49 events above 200 keV threshold after proton quenching
    - Second largest SN signal in SNO+

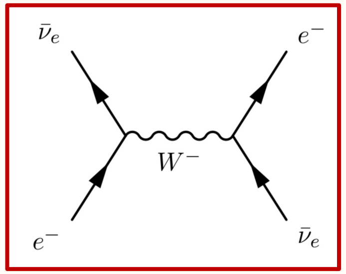


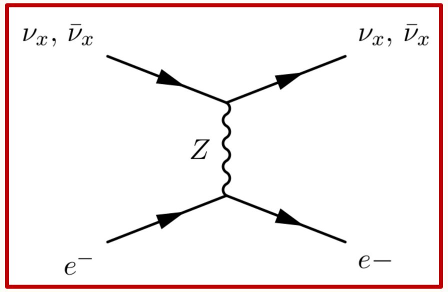


† $27 M_{\odot}$ progenitor CCSN with LS220 equation-of-state, 10 kpc away

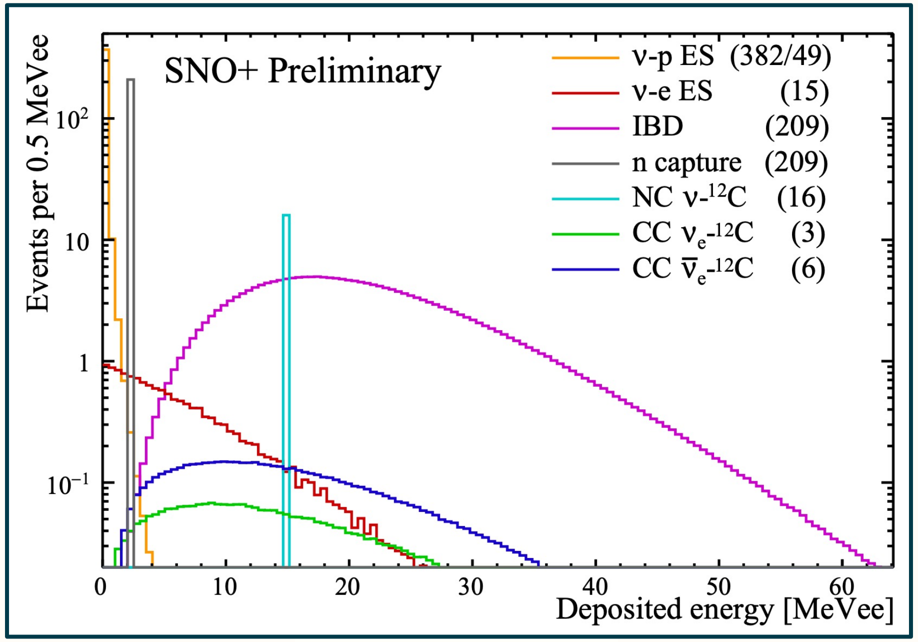
Other Interactions







- Flavour dependent cross-section
- ν_e and $\nu_e \rightarrow$ CC interactions
- $\nu_x \rightarrow$ NC interactions



$$\nu_e +^{12}\mathrm{C} \rightarrow^{12}\mathrm{N} + e^-$$

ν_e Charged Current on ^{12}C

$$\bar{\nu}_e +^{12}\mathrm{C} \rightarrow^{12}\mathrm{B} + e^+$$

$\bar{\nu}_e$ Charged Current on ^{12}C

$$\nu_e +^{12}\mathrm{C} \rightarrow^{12}\mathrm{C}^* \rightarrow^{12}\mathrm{C} + \gamma$$

ν_x Neutral Current on ^{12}C

- Distinctive 15.1 MeV excitation
- Cross-section measured by Karmen

SNEWS and SNEWS2

Super**N**ova **E**arly **W**arning **S**ystem

Currently listed experiments (on SNEWS2 website):

Water Cherenkov

Super-Kamiokande, KM3NeT, and IceCube

Liquid Scintillator

SNO+, KamLAND, and NOvA

Lead

HALO

Dark Matter Detectors

XENONnT, LZ, and PandaX-4T

Also listed on SNEWS website:

Borexino, LVD, MiniBooNE, and Daya Bay

Quenching

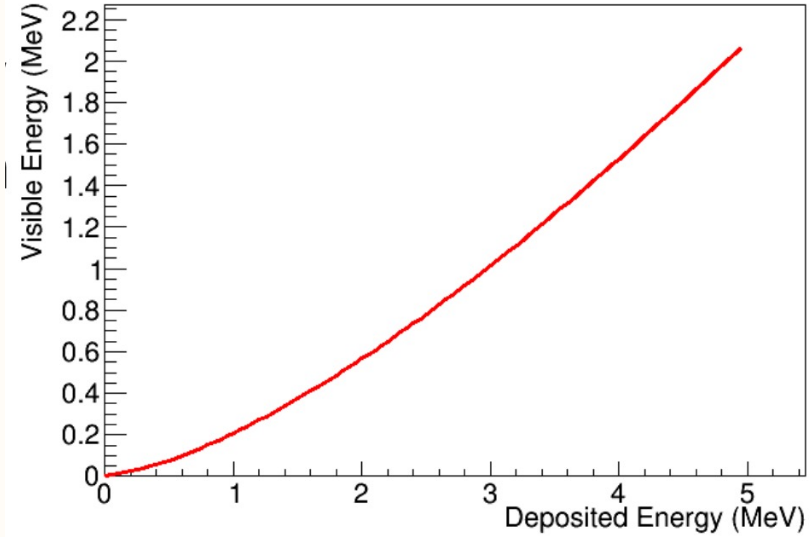
- Scintillator produces light via excitation and subsequent de-excitation.
- More ionising particles (protons) excite the particles such that less light is produced (Quenched)
- Modelled using Birks' Law
  - kB is Birks Constant which is material dependent
  - Has been measured for SNO+ scintillator

Observed energy

Deposited energy

$$\frac{d\epsilon}{dx} = \frac{\frac{dE}{dx}}{1 + k_B \frac{dE}{dx}}$$

0.0096 ± 0.0003 for SNO+ scintillator



Proc. Phys. Soc. A64 (1951) 874-877

Arxiv:1301.6403

SN Probability

arXiv:1309.0559